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STRAIN RATE EFFECTS ON MECHANICAL PROPERTIES OF FIBER COMPOSITES

Final Report - Part III

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16. Abstract

An experimental investigation was conducted to determine the strain rate effects in fiber composites. Unidirectional composite specimens of boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar/epoxy were tested at strain rates of up to 27 ϵ/sec to determine longitudinal, transverse and intralaminar (in-plane) shear properties. In the longitudinal direction the Kevlar/epoxy shows a definite increase in both modulus and strength with strain rate. In the transverse direction, a general trend toward higher strength with strain rate is noticed. The intralaminar shear moduli and strengths of boron/epoxy and graphite/epoxy show a definite rise with strain rate.

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FOREWORD

This is the Final Report on IIT Research Institute Project No. D6073-IV, "Strain Rate Effects on Mechanical Properties of Fiber Composites," prepared by IITRI for NASA-Lewis Research Center, under Contract No. NAS3-16766. The work described in this report was conducted in the period July 1, 1974 to February 29, 1976. The work performed in the preceding period August 1, 1972 to June 30, 1974 was reported in the First Interim Report, NASA CR-134826 dated March 1975. Dr. C.C. Chamis was the NASA-Lewis Project Manager. Dr. I.M. Daniel of IITRI was the principal investigator. Additional contributions to the work reported herein were made by Dr. T. Liber and Messrs. R. LaBedz and M. Senninger.

Respectfully submitted,
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STRAIN RATE EFFECTS ON MECHANICAL PROPERTIES OF FIBER COMPOSITES

ABSTRACT

An experimental investigation was conducted to determine the strain rate effects in fiber composites. Unidirectional composite specimens of boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar/epoxy were tested at tensile strain rates of up to 27 ε/sec to determine longitudinal, transverse and intralaminar (in-plane) shear properties. In the longitudinal direction the Kevlar/epoxy shows a definite increase in both modulus and strength with strain rate. In the transverse direction a general trend toward higher strength with strain rate is noticed. The intralaminar shear moduli and strengths of boron/epoxy and graphite/epoxy show a definite rise with strain rate.

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STRAIN RATE EFFECTS ON MECHANICAL PROPERTIES OF FIBER COMPOSITES

1.0 INTRODUCTION

Most composite materials of interest to structural applications have been fully characterized under static loading conditions. Extensive data were presented in prior reports.[1,2] Very little work on composite properties at high rates of loading has been reported. The need for characterization at high loading rates arises from the fact that in problems of projectile impact and foreign object damage (FOD) the material experiences very high strain rates. Strain rates in the range of 250-650 /sec were measured in impacted uniaxial and angle-ply boron/epoxy and graphite/epoxy laminates in the preceding task. One would expect that stiffnesses and ultimate values, especially those governed by the viscoelastic matrix, would be time and rate dependent. The objective of this task was to measure the stiffness, strength and ultimate strain of unidirectional composites subjected to high rates of loading. The materials investigated were the same ones used in the two previous tasks, i.e., boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar 49/epoxy.

2.0 EXPERIMENTAL PROCEDURES

Longitudinal (0-degree) tensile properties were obtained using 6-ply coupons 1.27 cm (0.50 in.) wide with a 5.08 cm (2 in.) gage length and tabbed with fiberglass tabs. Transverse (90-degree) tensile properties were obtained using 8-ply coupons, 1.27 cm (0.50 in.) wide with a 7.62 cm (3 in.) gage length. These specimens were instrumented with a two-gage rosette on each side of the specimen. In-plane shear properties were obtained by using 10-degree off-axis coupons, 6-ply thick, 1.27 cm (0.50 in.) wide with a 7.62 cm (3 in.) gage length. They were instrumented with a three-gage rosette on each side of the specimen. Boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar 49/epoxy specimens for uniaxial tensile testing at 0-, 90- and 10-degrees to the fibers were prepared and instrumented.

These specimens were tested in uniaxial tension at various strain rates. An MTS electro-hydraulic closed-loop system capable of delivering a wide range of input pulses at velocities up to 5.1 ms^{-1} (12,000 in/min) was used. Special fixtures were designed and built for each type of test. One tabbed end of the specimen was clamped between two metal grips and connected through a pin to a clevis link attached to the upper crosshead of the loading frame. At the bottom end two additional fiberglass tabs extending beyond the original tabs were bonded on. These secondary tabs were connected through a pin to a load link which in turn was connected to the bottom clevis link attached to the moving ram. The fixture allowed the ram to accelerate for approximately 6.3 mm (1/4 in.) before transmitting load to the specimen. This allows for a more uniform rate of loading. A 10-degree specimen with the loading fixture mounted in the machine is shown in Fig. 1. The dynamic load initially was measured with a piezoelectric crystal load cell, however, it was found that at the higher strain rates the load signals were perturbed by resonant oscillations. Subsequently,

load measurement was done by means of an aluminum link instrumented with strain gages and connected in series with the specimen. Strain gages from the test specimen and the load cell were recorded on oscilloscopes. The overall experimental setup is shown in Fig. 2.

In all cases above a few quasistatic tests were conducted to provide a reference at very slow rates for specimens of identical geometry. These quasistatic results were used to supplement previously obtained similar results.[1,2]

3.0 RESULTS AND DISCUSSION

Typical load and strain oscilloscope signals for the $[0_6]$ boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar 49/epoxy specimens are shown in Figs. 3 through 8. Results from these tests as well as corresponding static tests are tabulated in Table 1. Results for boron/epoxy show no significant changes in modulus but some increase in strength at the higher strain rates. The ultimate strain remains relatively constant, with one exception at the 5.3 ε/sec strain rate where the limit strain is 8.4×10^{-3}. In the case of graphite/epoxy there is a slight increase in modulus with strain rate but no significant changes in strength or limit strain. In the case of S-glass/epoxy there are no significant changes in modulus or strength but some trend towards higher ultimate strain at the higher rates of loading. Kevlar 49/epoxy shows a definite increase in modulus with strain rate and some increase in strength. The ultimate strain at the higher rates of loading are slightly lower than for static loading. In this series of tests where the properties of the composites are dominated by the fibers trends of properties with increasing strain rate are barely detectable. This is due primarily to the fact that the properties of the fiber materials, with the possible exception of Kevlar, are not very rate dependent, and due to the small number of specimens.

Unidirectional eight-ply 90-degree specimens of the four materials above were tested in tension to failure statically and at various high strain rates. A more sensitive load cell link was designed and used in these tests. Strain rates ranged from quasistatic to 27 ε/sec. Typical load and strain records are shown in Figs. 9 through 15. Results from these tests as well as corresponding static tests are tabulated in Table 2

Table 1

LONGITUDINAL PROPERTIES OF UNIDIRECTIONAL COMPOSITES AT VARIOUS STRAIN RATES

Material	Average Strain Rate (ε/sec)	Maximum Strain Rate (ε/sec)	Time to Failure (ms)	Modulus E_{11} GPa (10^6 psi)	Poisson's Ratio ν_{12}	Strength S_{11T} MPa(ksi)	Ult. Strain ($10^{-3}\varepsilon$) ε_{11}^u
Boron/Epoxy	1.4×10^{-4}	1.4×10^{-4}	50×10^3	201 (29.2)	0.17	1375 (199)	7.0
	4.2×10^{-4}	4.2×10^{-4}	17×10^3	192 (27.9)	0.18	1350 (196)	7.2
	1.7	1.8	4	215 (31.1)	0.22	-	-
	1.8	2.0	3.6	212 (30.7)	0.21	1216 (176)	6.8
	1.8	2.7	3.9	204 (29.6)	0.23	1457 (211)	7.2
	5.3	5.3	1.6	201 (29.2)	0.20	1622 (235)	8.4
	10.3	10.3	0.7	198 (28.7)	0.20	1430 (207)	6.9
Graphite/ Epoxy	4.2×10^{-4}	4.2×10^{-4}	12×10^3	196 (28.4)	0.25	980 (142)	5.1
	4.2×10^{-4}	4.2×10^{-4}	14×10^3	202 (29.2)	0.26	1220 (177)	6.0
	1.4	1.9	3.8	208 (30.1)	0.14	1007 (146)	5.3
	2.6	3.8	2.0	217 (31.5)	0.17	1159 (168)	6.0
	3.1	5.0	1.6	207 (30.0)	0.23	1028 (149)	5.3
S-Glass/ Epoxy	1.4×10^{-4}	1.4×10^{-4}	250×10^3	50 (7.2)	0.29	1773 (257)	35.6
	4.2×10^{-4}	4.2×10^{-4}	77×10^3	53 (7.7)	0.28	1545 (224)	32.5
	4.5	4.5	4.6	52 (7.6)	0.22	1290 (187)	30.5
	4.6	4.6	7.2	48 (7.0)	0.25	1552 (225)	37.5
	4.2	4.8	7.3	47 (6.8)	0.26	1332 (193)	35.1
	16.0	16.0	2.3	50 (7.3)	0.28	1780 (258)	38.4
	18.8	18.8	2.0	50 (7.3)	0.26	1787 (259)	38.6
Kevlar 49/ Epoxy	1.4×10^{-4}	1.4×10^{-4}	138×10^3	69 (10.0)	0.40	1425 (207)	19.4
	4.2×10^{-4}	4.2×10^{-4}	48×10^3	72 (10.5)	0.33	1533 (222)	20.0
	3.0	9.6	4.1	79 (11.4)	0.40	1204 (175)	18.9
	3.2	11.7	4.0	78 (11.3)	0.43	1323 (192)	18.6
	15.0	15.0	1.1	83 (12.0)	0.38	1546 (224)	18.5
	15.0	15.0	1.2	83 (12.0)	0.33	1622 (235)	19.0

Table 2

TRANSVERSE PROPERTIES OF UNIDIRECTIONAL COMPOSITES AT VARIOUS STRAIN RATES

Material	Average Strain Rate (ε/sec)	Maximum Strain Rate (ε/sec)	Time to Failure (ms)	Modulus E_{22} GPa (10^6 psi)	Poisson's Ratio ν_{21}	Strength S_{22T} MPa (ksi)	Ult. Strain $(10^{-3}\varepsilon)\varepsilon_{22}^{u}$
Boron/Epoxy	1.4×10^{-4}	1.4×10^{-4}	20×10^3	22.0(3.1)	0.02	56 (8.1)	2.9
	2.8×10^{-4}	2.8×10^{-4}	10×10^3	19.0(2.8)	0.014	56 (8.1)	2.9
	0.23	0.25	14.0	19.0(2.)	0.001	47 (6.8)	2.7
	0.55	0.60	8.6	15.2(2.2)	0.007	55 (8.0)	3.3
	0.60	0.70	8.8	14.7(2.1)	0.007	59 (8.5)	3.7
	4.5	5.8	0.65	-	0.012	-	3.0
	14	19	0.35	15.9(2.3)	0.011	78(11.3)	4.5
	20	27	0.35	13.4(1.9)	0.013	76(11.0)	5.7
Graphite/ Epoxy	2.8×10^{-4}	2.8×10^{-4}	13×10^3	8.3(1.2)	0.005	30 (4.4)	3.5
	2.8×10^{-4}	2.8×10^{-4}	10×10^3	7.8(1.1)	0.007	23 (3.3)	2.9
	0.35	0.75	7.5	7.1(1.0)	0.009	25 (3.6)	3.1
	0.35	0.80	7.4	6.9(1.03)	0.011	30 (4.4)	3.7
	8.2	10.0	0.50	9.3(1.35)	0.005	32 (4.7)	3.6
	8.7	10.3	0.55	9.1(1.32)	0.004	32 (4.7)	3.4
S-Glass/ Epoxy	1.4×10^{-4}	1.4×10^{-4}	33×10^3	19 (2.8)	0.10	79(11.4)	4.6
	2.8×10^{-4}	2.8×10^{-4}	12×10^3	21 (3.1)	0.10	61(8.8)	3.3
	0.40	0.50	9.7	20.6(3.0)	0.08	81(11.7)	4.0
	0.40	0.60	10	20.2(2.9)	0.09	78(11.3)	4.0
	6.3	6.3	0.90	17.1(2.5)	0.07	75(11.0)	4.9
	6.8	6.8	0.70	-	0.09	-	3.1
	13	13	0.70	-	0.09	-	4.5
	11	18	0.55	16.2(2.3)	0.06	82(12.0)	5.3

In the boron/epoxy the modulus and strength are generally lower than corresponding static values, except for the highest strain rates, 19 and 27 ε/sec, where the strength is higher than the static one. The ultimate strain at the high strain rates is, with one exception, much higher than the static values. There is no plausible explanation for these results. In the graphite/epoxy there is some increase in modulus and strength at the higher rates of loading accompanied by an increase in limit strain. In the S-glass/epoxy there seems to be an unlikely reduction in modulus with strain rate, a fact which may not be significant. There is some trend toward higher strength with increasing strain rate. No significant trends in limit strain are apparent. The Kevlar 49/epoxy specimens were too fragile to handle in the electrohydraulic machine and failed at very low loads. The results above do not show any drastic changes of properties with strain rate although these properties are governed by the matrix, which should be more rate dependent.

Unidirectional six-ply specimens of the four materials above were tested in uniaxial tension at 10-degrees to the fiber direction statically and at various high strain rates. These specimens were instrumented with a three-gage rosette on each side. Signals from the load cell and from the longitudinal, transverse and 45-degree gages were recorded on four oscilloscopes. Axial strain rates ranged from quasistatic to 7.7 ε/sec. Typical load and strain records are shown in Figs. 16 through 19. Results from these tests as well as corresponding static tests are tabulated in Table 3. In the boron/epoxy both the in-plane shear modulus and shear strength show an increase with strain rate. The limit shear strain at the high rates of loading, however, is lower than the corresponding static one. The trends in graphite/epoxy are similar to those in boron/epoxy, with shear modulus and shear strength increasing with strain rate. No significant trends

Table 3

INTRALAMINAR SHEAR PROPERTIES OF UNIDIRECTIONAL COMPOSITES AT HIGH STRAIN RATES

Material	Average Strain Rate (ε/sec)	Initial Strain Rate (ε/sec)	Time to Failure (ms)	Shear Modulus G_{12} GPa(10^6 psi)	Shear Strength S_{12} MPa (ksi)	Ultimate Shear Strain ε_{12} ($10^{-3}\varepsilon$)
Boron/Epoxy	1.4×10^{-4}	1.4×10^{-4}	33×10^3	5.4 (0.80)	62.3 (9.1)	7.26
	2.8×10^{-4}	2.8×10^{-4}	17×10^3	6.2 (0.90)	56.9 (8.2)	7.60
	-	-	6.5	-	56.5 (8.2)	-
	0.59	0.48	6.6	6.8 (0.99)	65.9 (9.6)	5.43
	0.57	0.47	6.5	7.0 (1.02)	66.1 (9.6)	6.71
	2.8	4.1	1.5	7.9 (1.14)	76.7 (11.1)	6.99
	2.6	5.7	1.0	7.2 (1.04)	62.5 (9.1)	5.46
	2.7	6.3	1.4	8.1 (1.18)	76.3 (11.1)	5.42
	3.3	6.8	1.2	6.7 (0.97)	72.9 (10.6)	7.21
	3.9	7.7	0.8	7.7 (1.12)	-	-
Graphite/ Epoxy	2.8×10^{-4}	2.8×10^{-4}	13×10^3	5.8 (0.84)	53.7 (7.8)	5.26
	2.8×10^{-4}	2.8×10^{-4}	7.5×10^3	6.1 (0.89)	34.8 (5.1)	3.10
	0.15	0.28	9.0	6.2 (0.90)	-	-
	-	-	6.7	-	62.8 (9.1)	-
	0.41	0.41	6.8	7.5 (1.08)	56.4 (8.2)	3.10
	0.52	0.50	6.0	7.7 (1.11)	59.1 (8.6)	5.45
	2.4	4.0	1.2	7.6 (1.10)	68.2 (9.9)	4.27
	2.3	5.4	1.1	7.2 (1.05)	65.0 (9.4)	3.46
S-Glass/ Epoxy	2.8×10^{-4}	2.8×10^{-4}	17×10^3	4.5 (0.65)	59.0 (8.6)	7.0
	0.34	0.29	15.6	4.3 (0.62)	-	-
	-	-	4.8	-	73.1 (10.6)	-
	2.8	2.8	4.2	-	67.8 (9.8)	-
	12.6	20	2.1	4.3 (0.62)	56.6 (8.2)	13.0
Kevlar 49/ Epoxy	2.8×10^{-4}	2.8×10^{-4}	12×10^3	1.84 (0.27)	16.4 (2.37)	4.65
	0.29	0.23	9.2	1.97 (0.29)	12.2 (1.77)	4.25
	0.30	0.29	10.0	2.03 (0.29)	15.3 (2.22)	4.99
	0.44	0.44	7.6	1.90 (0.28)	13.2 (1.91)	5.40
	14	12.9	0.75	1.52 (0.22)	16.8 (2.44)	14.74

were noticed in the S-glass/epoxy and Kevlar/epoxy materials. Properties obtained at high strain rates were comparable with those obtained statically for the same batch of specimens. However, these properties are lower than those obtained initially for the same materials[2], indicating aging and deterioration of the prepreg materials used. It was not possible to obtain a fresh batch of these materials as the matrix resin ERLA 4617 was no longer available.

4.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

An electrohydraulic system was set up for testing unidirectional composite coupons in tension at high strain rates. Four materials were investigated, boron/epoxy, graphite/epoxy, S-glass/epoxy and Kevlar 49/epoxy. Longitudinal, transverse and in-plane shear properties, including modulus, Poisson's ratio, strength and ultimate strain, were determined by testing 0-, 90- and 10-degree unidirectional coupons. Strains were measured by means of strain gages bonded on the coupons and loads were measured by means of a strain gage load cell mounted in series with the specimen. Signals from all strain gages were recorded on oscilloscopes.

In the case of 0-degree properties which are governed by the fibers, variation of properties with strain rate are barely detectable. The boron/epoxy shows some increase in strength at the higher strain rates but no significant changes in modulus or ultimate strain. In the graphite/epoxy there appears to be a slight increase in modulus with strain tate but no significant changes in strength or ultimate strain. In the S-glass/epoxy there are no significant changes in modulus or strength but some trend toward higher ultimate strains at the higher rates of loading. The Kevlar 49/epoxy shows a definite increase in modulus and strength with strain rate because the fibers in this case have more rate dependent properties.

One would expect that the 90-degree properties, which are governed by the properties of the matrix materials, would be much more rate dependent. In the boron/epoxy there is an unexplainable trend toward lower values in modulus, however, the strength and limit strain in general increase slightly with strain rate. In the graphite/epoxy there is a general slight increase in modulus, strength and ultimate strain. In the S-glass/epoxy there appear to be two contrary trends toward lower modulus and higher strength

with increasing strain rate, however, these may not be significant.

The in-plane shear properties are also governed by those of the matrix material and as such they should be rate dependent. Both the boron/epoxy and graphite/epoxy show definite trends of increasing shear modulus and shear strength with strain rate. The increase in strength at the high strain rates over the static values is approximately 15 percent. No significant trends were detected in the S-glass/epoxy and Kevlar/epoxy materials. There is some question on the validity of results from these two materials as the specimens were prepared from an aged batch of prepreg material.

In general, properties of unidirectional composites such as modulus and strength tend to increase with strain rate. A more systematic series of tests with more replications per test is necessary to establish these trends in a reliable quantitative manner. The rate of testing must be increased further by at least an order of magntiude to achieve conditions comparable to those existing in impacted laminates. It is anticipated that strain rate effects will be more pronounced at higher strain rates.

To properly evaluate results of dynamic loading of composites the basic material properties over pertinent time-scales, i.e., high strain rates, must be determined. The need exists for continuing and extending the work conducted under the task reported here. A systematic series of tests with more replications per test is needed. Compressive properties and properties of angle-ply laminates must be added. The present electrohydraulic system must be modified to increase the rate of loading by at least one order of magnitude, to achieve rates comprable to those encountered under impact loading. It is anticipated that strain rate effects will be more pronounced at higher strain rates.

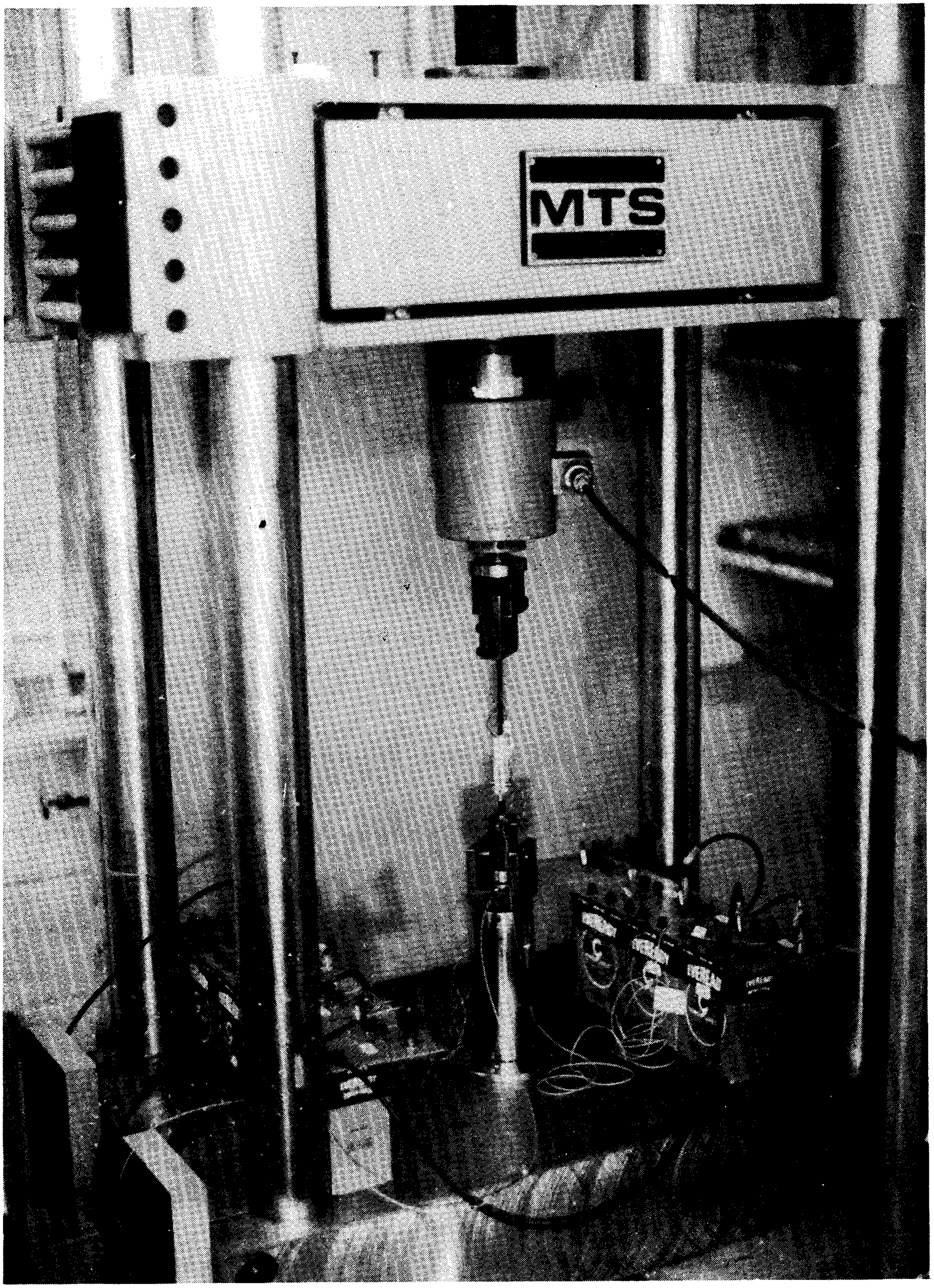


Fig. 1 UNIDIRECTIONAL 10-DEGREE OFF-AXIS SPECIMEN MOUNTED IN MACHINE FOR TESTING AT HIGH STRAIN RATES

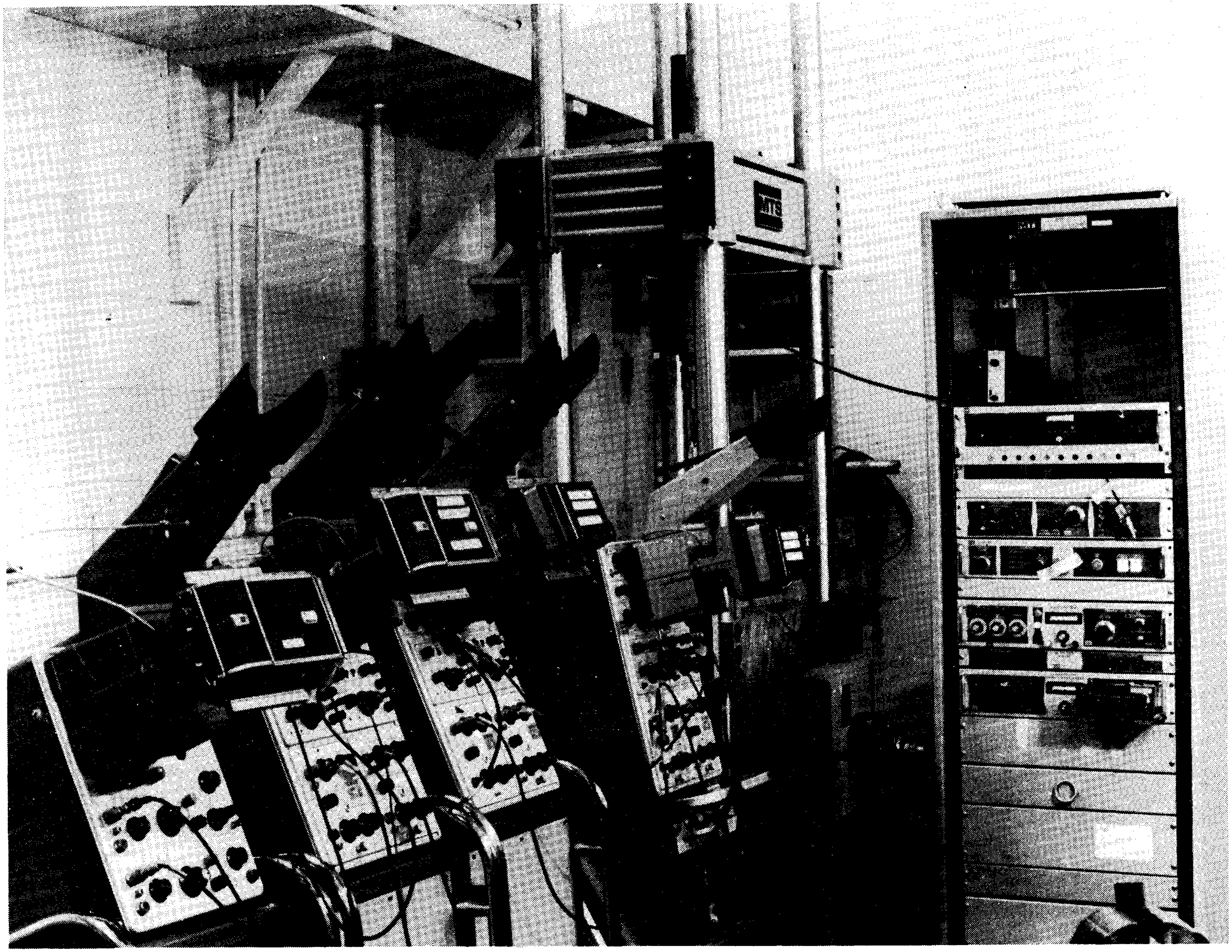


Fig. 2 EXPERIMENTAL SETUP FOR TESTING COMPOSITE SPECIMENS AT HIGH STRAIN RATES IN ELECTROHYDRAULIC TESTING MACHINE

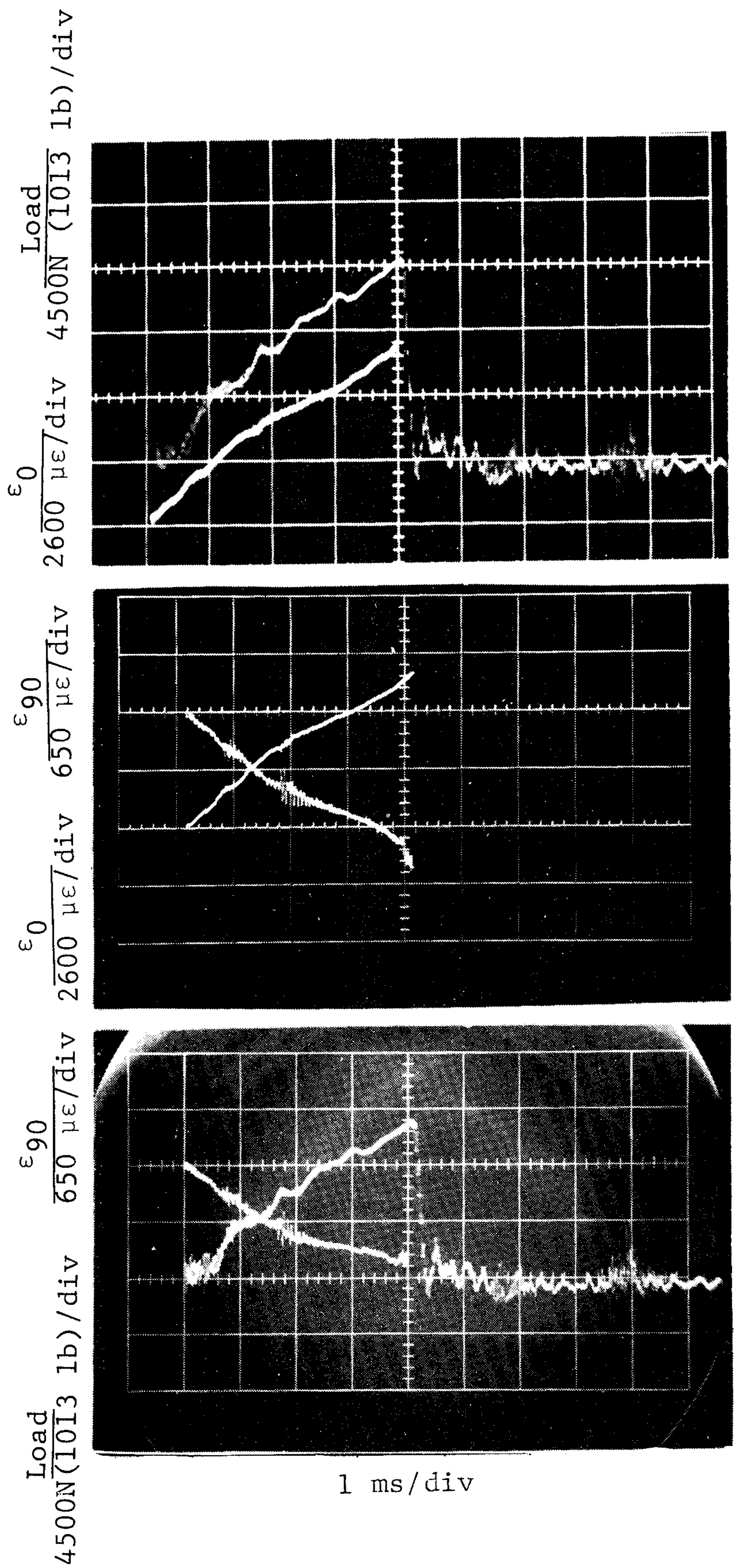
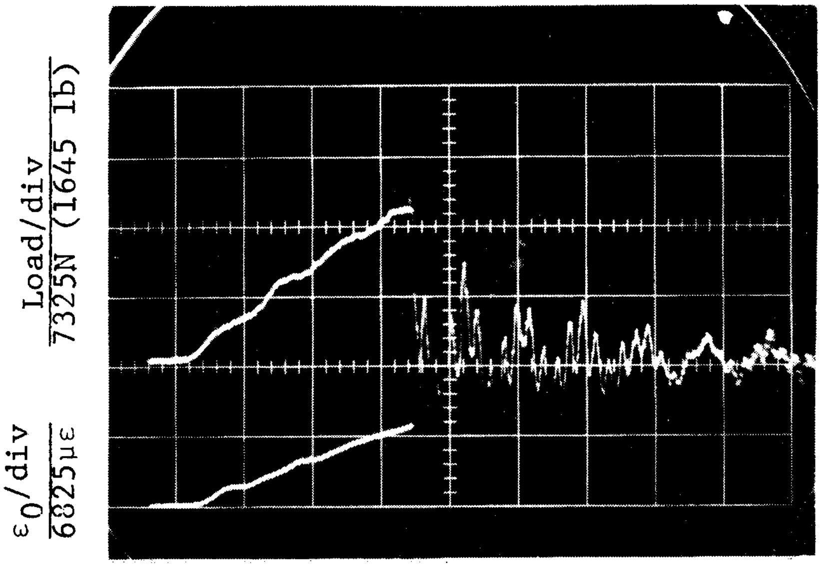
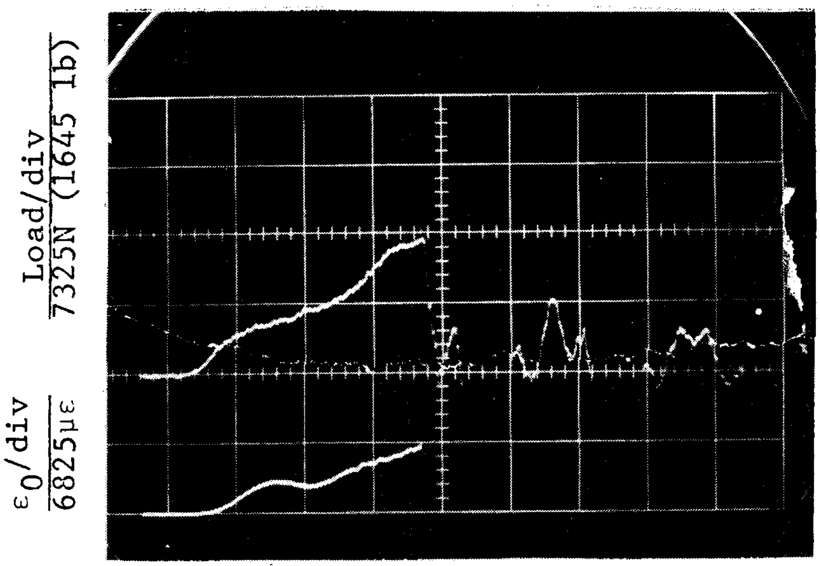


Fig. 3 LOAD AND STRAIN RECORDS FOR $[0_6]$ BORON/EPOXY SPECIMEN LOADED AT A STRAIN RATE OF 2.7 ε/sec.



500 μs/div



200 μs/div

Fig. 4 LOAD AND STRAIN RECORDS FOR $[0_6]$ BORON/ EPOXY SPECIMENS LOADED IN TENSION AT STRAIN RATES OF 5.3 ε/sec and 10.3 ε/sec.

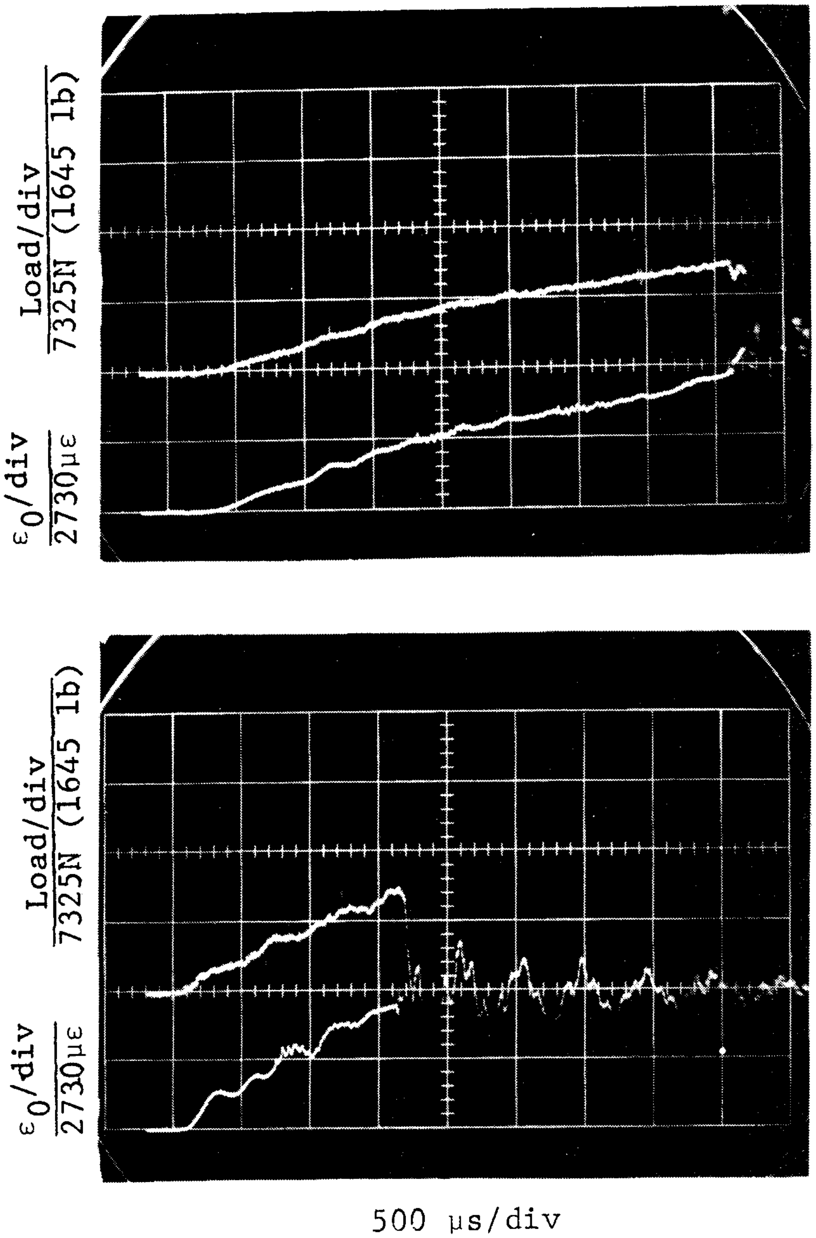


Fig. 5 LOAD AND STRAIN RECORDS FOR $[0_6]$ GRAPHITE/EPOXY SPECIMENS LOADED IN TENSION AT STRAIN RATES OF 1.9 ε/sec and 5.0 ε/sec.

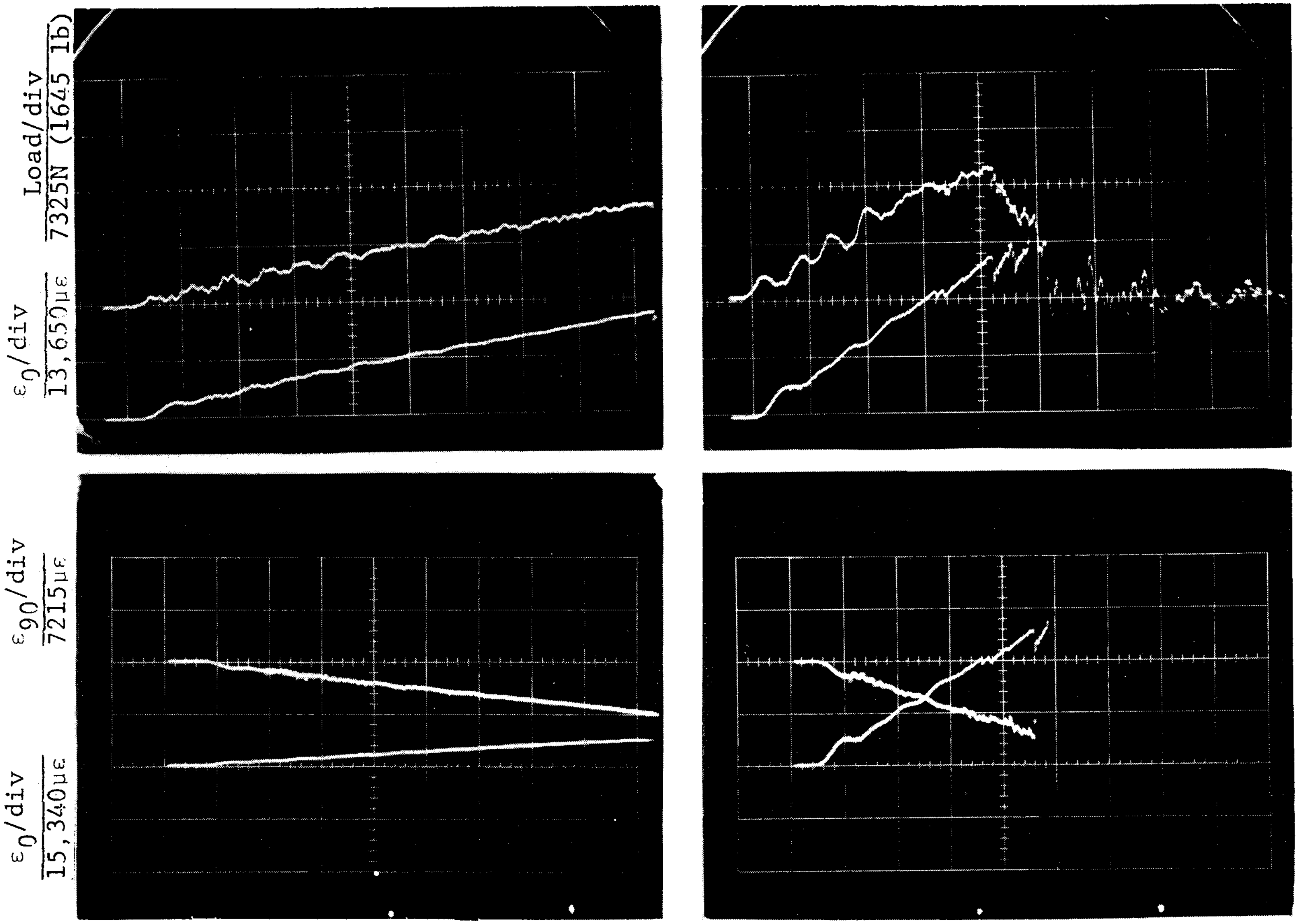


Fig. 6 LOAD AND STRAIN RECORDS FOR $[0_6]$ S-GLASS/EPOXY SPECIMENS LOADED IN TENSION AT STRAIN RATES OF 4.5 ε/sec and 18.8 ε/sec (Sweep: 500 μs/div).

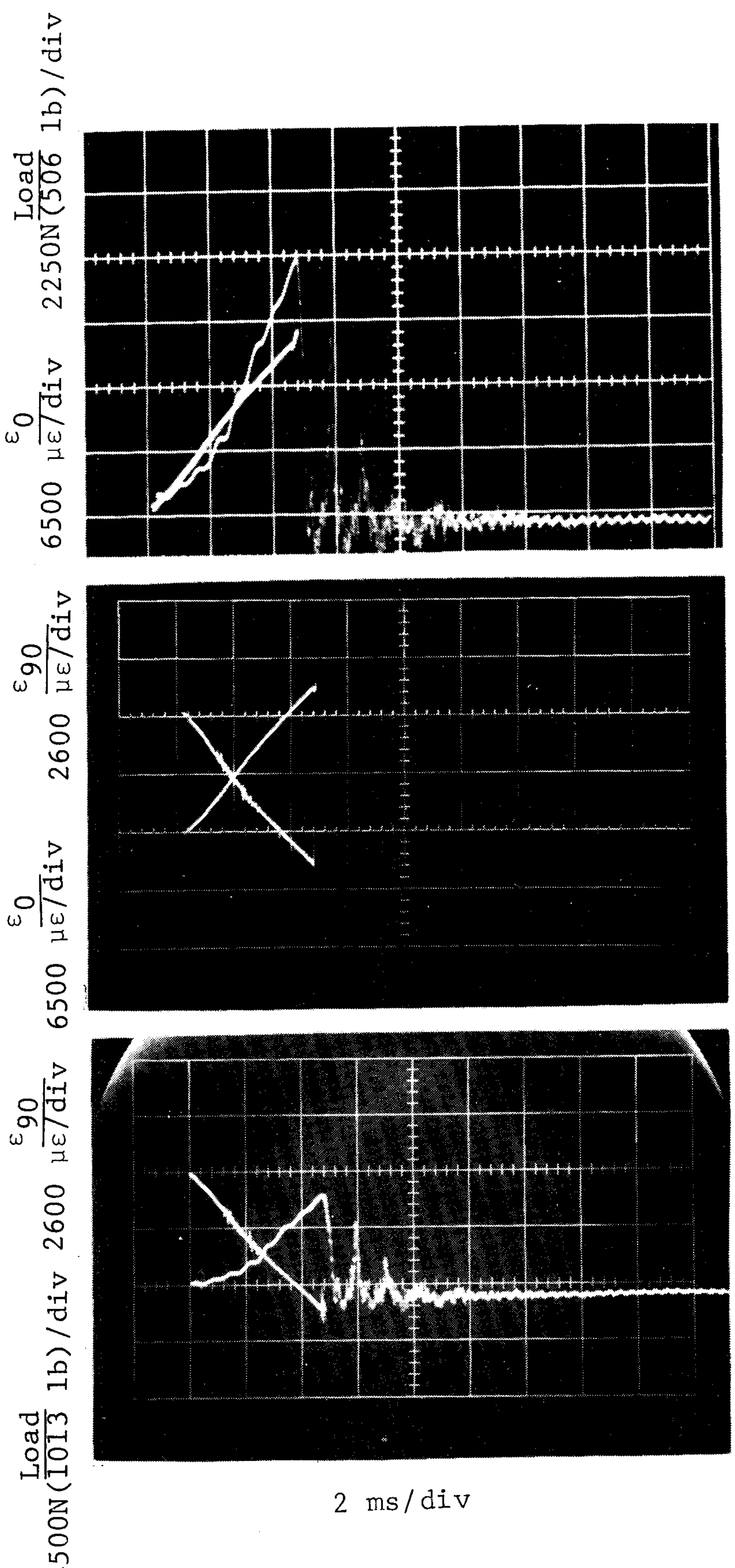


Fig. 7 LOAD AND STRAIN RECORDS FOR $[0_6]$ KEVLAR/EPOXY SPECIMEN LOADED AT A STRAIN RATE OF 4.0 ε/sec.

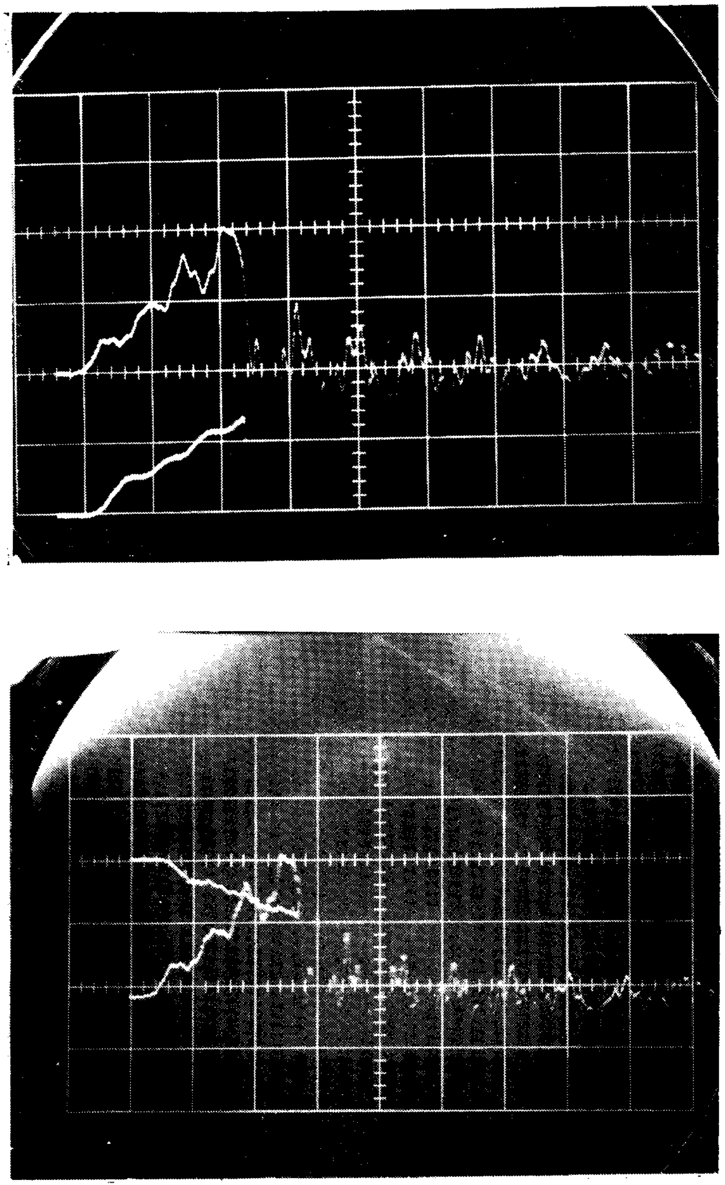


Fig. 8 LOAD AND STRAIN RECORDS FOR $[0_6]$ KEVLAR/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 15 ε/sec.

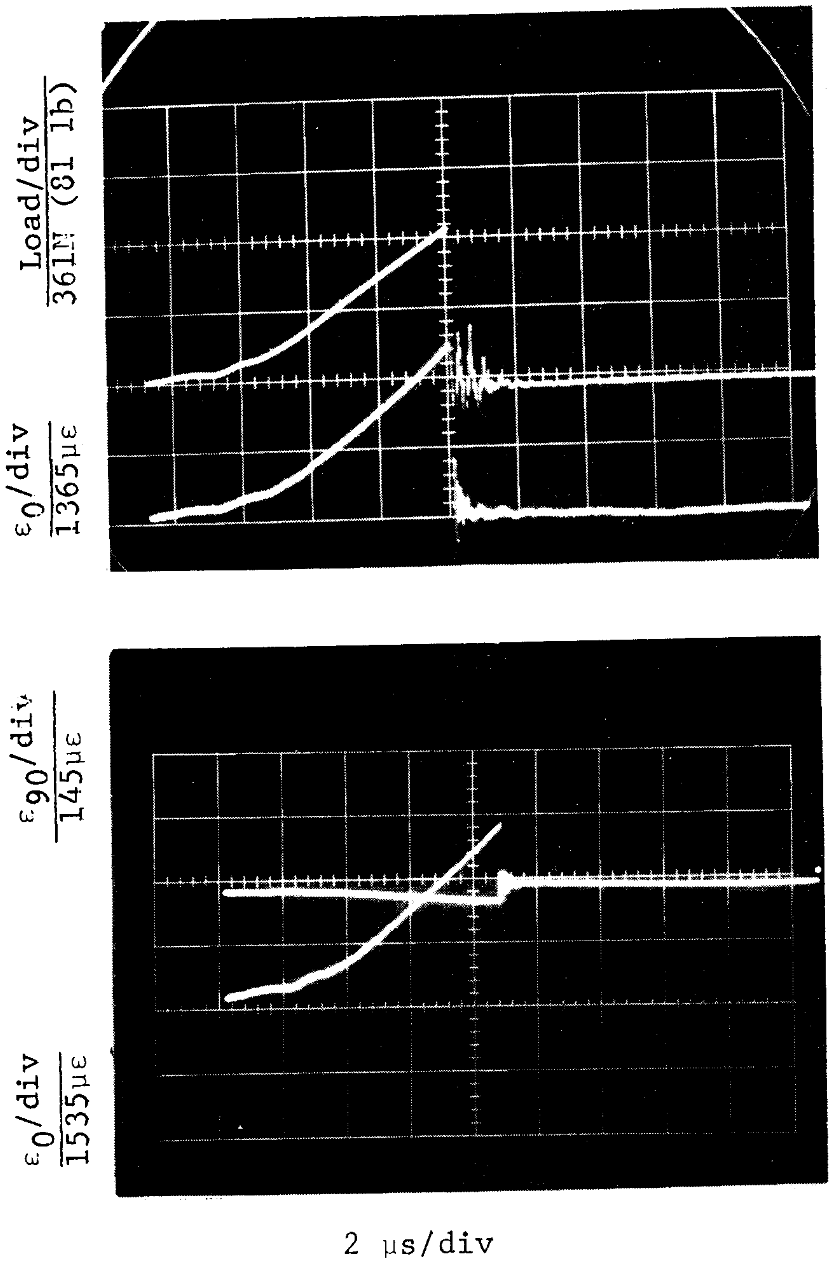


Fig. 9 LOAD AND STRAIN RECORDS FOR $[90_8]$ BORON/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 0.70 ε/sec.

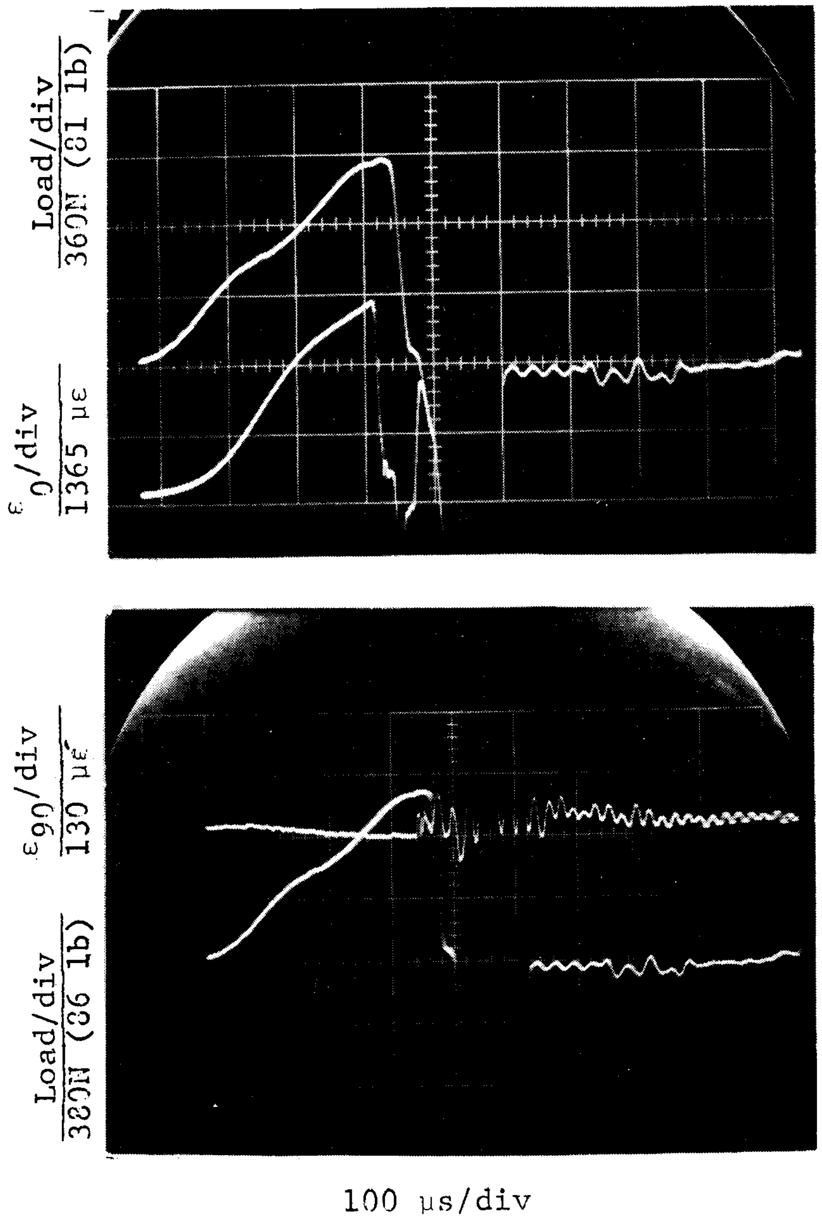
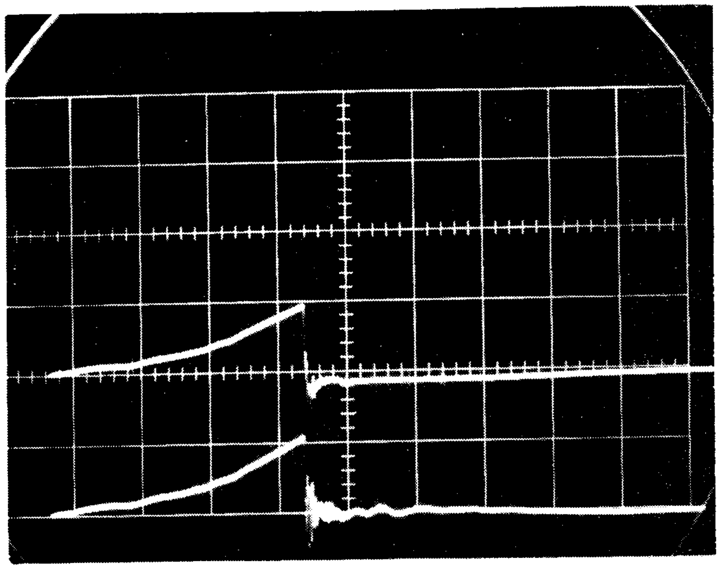


Fig. 10 LOAD AND STRAIN RECORDS FOR [90_8] BORON/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 19 ε/sec.

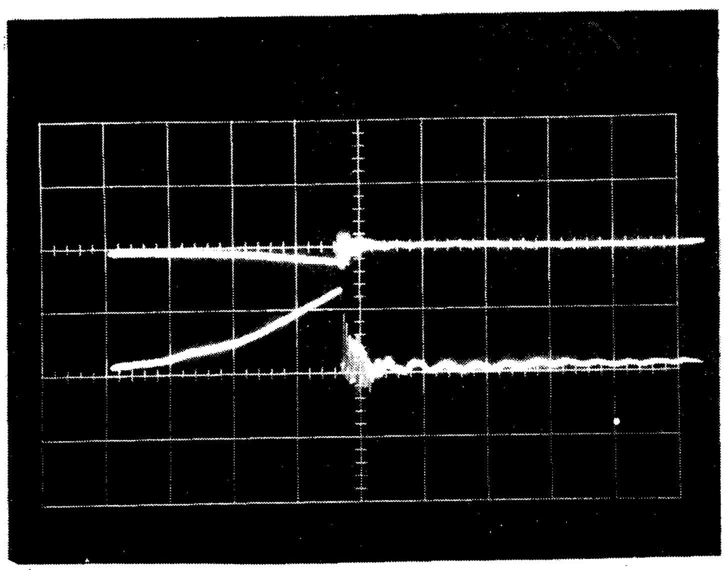
Load/div $\overline{361N\ (81\ lb)}$

ε_0/div $\overline{2730\mu\varepsilon}$



ε_{90}/div $\overline{145\mu\varepsilon}$

ε_0/div $\overline{3070\mu\varepsilon}$



2 μs/div

Fig 11 LOAD AND STRAIN RECORDS FOR $[90_8]$ GRAPHITE/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 0.80 ε/sec.

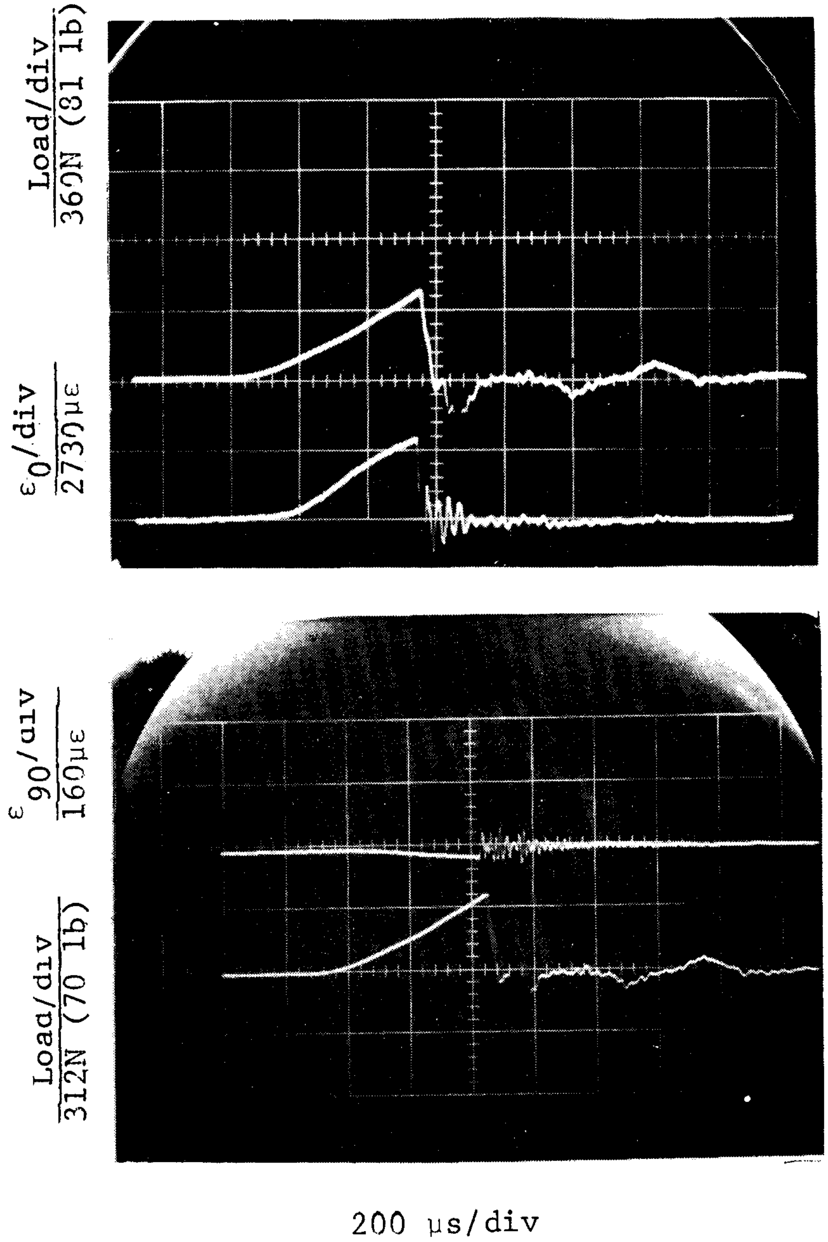


Fig. 12 LOAD AND STRAIN RECORDS FOR $[90_8]$ GRAPHITE/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 10 ε/sec.

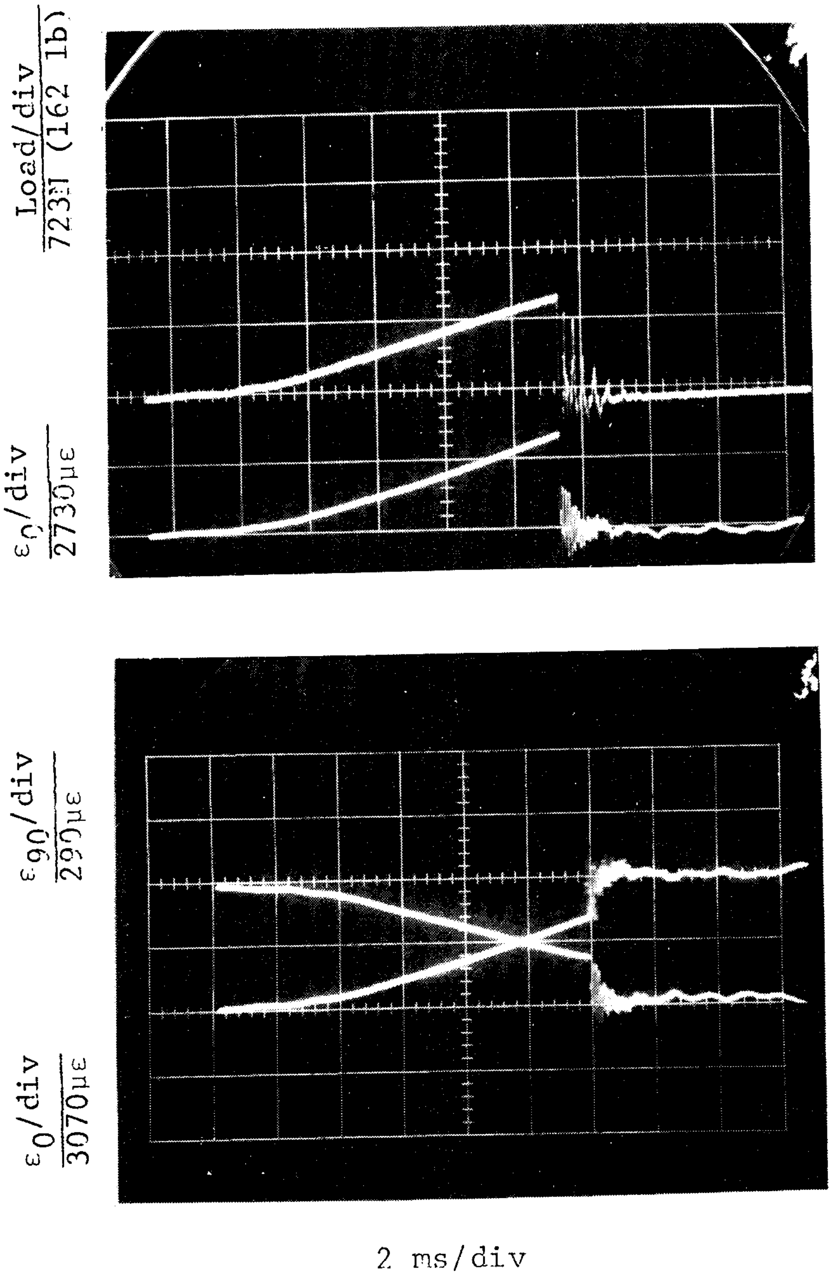


Fig. 13 LOAD AND STRAIN RECORDS FOR $[90_8]$ S-GLASS/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 0.50 ε/sec.

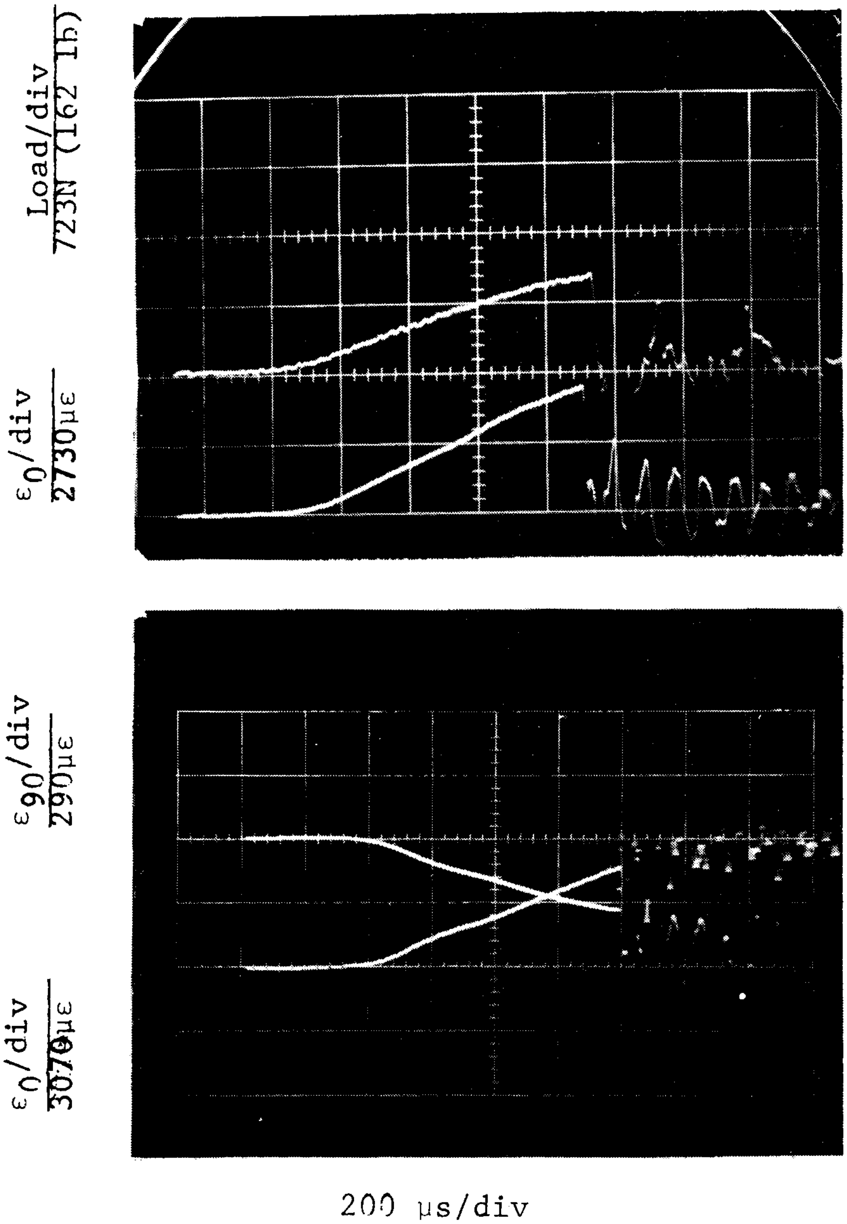


Fig. 14 LOAD AND STRAIN RECORDS FOR $[90_8]$ S-GLASS/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 6.3 ε/sec.

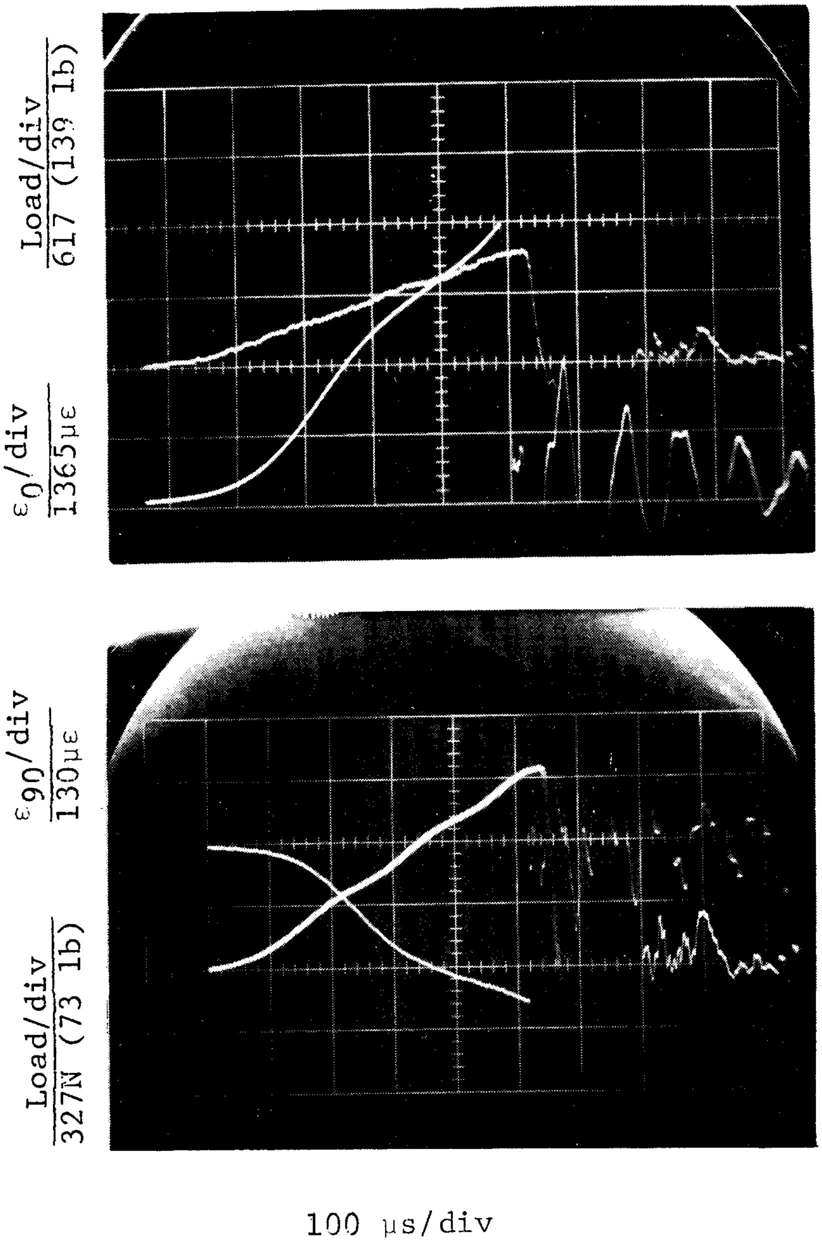


Fig. 15 LOAD AND STRAIN RECORDS FOR $[90_8]$ S-GLASS/EPOXY SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 18 ε/sec.

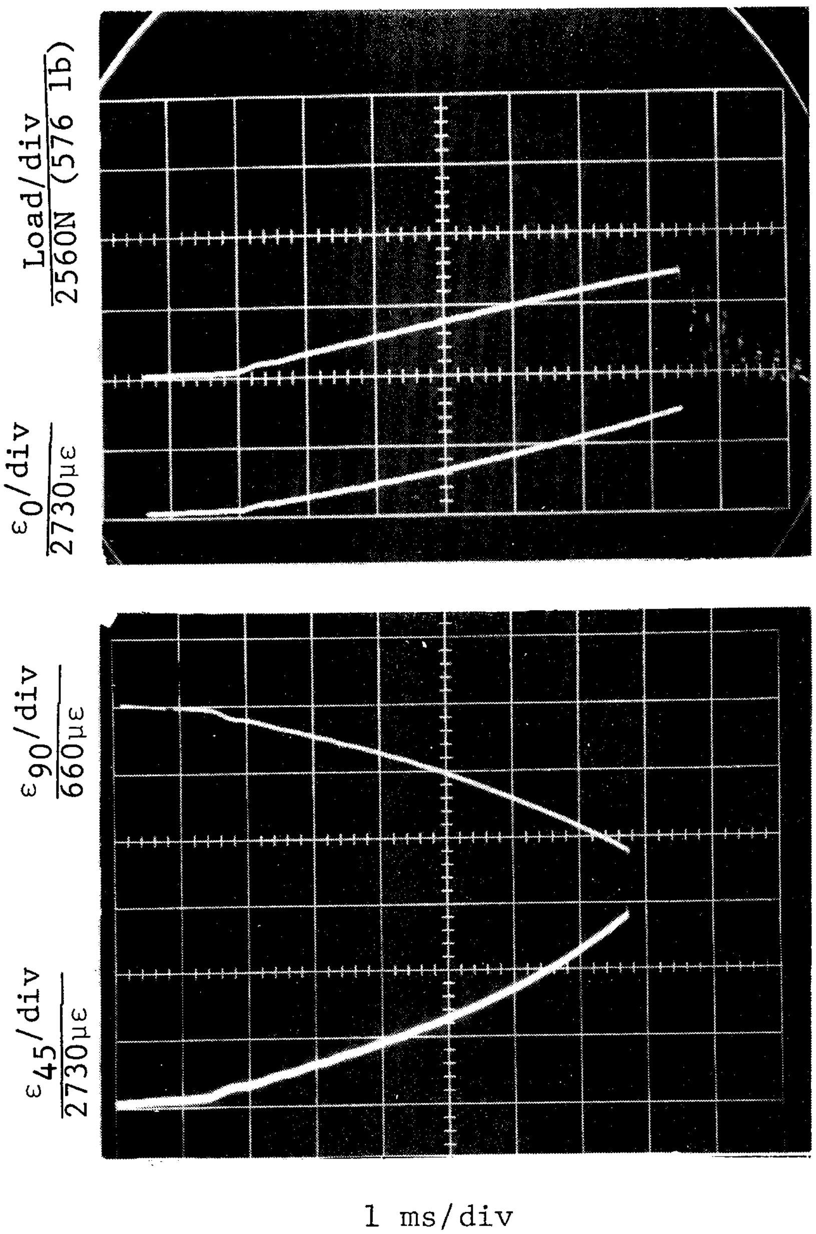


Fig. 16 LOAD AND STRAIN RECORDS FOR $[10_6]$ BORON/EPOXY OFF-AXIS SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 0.57 ε/sec.

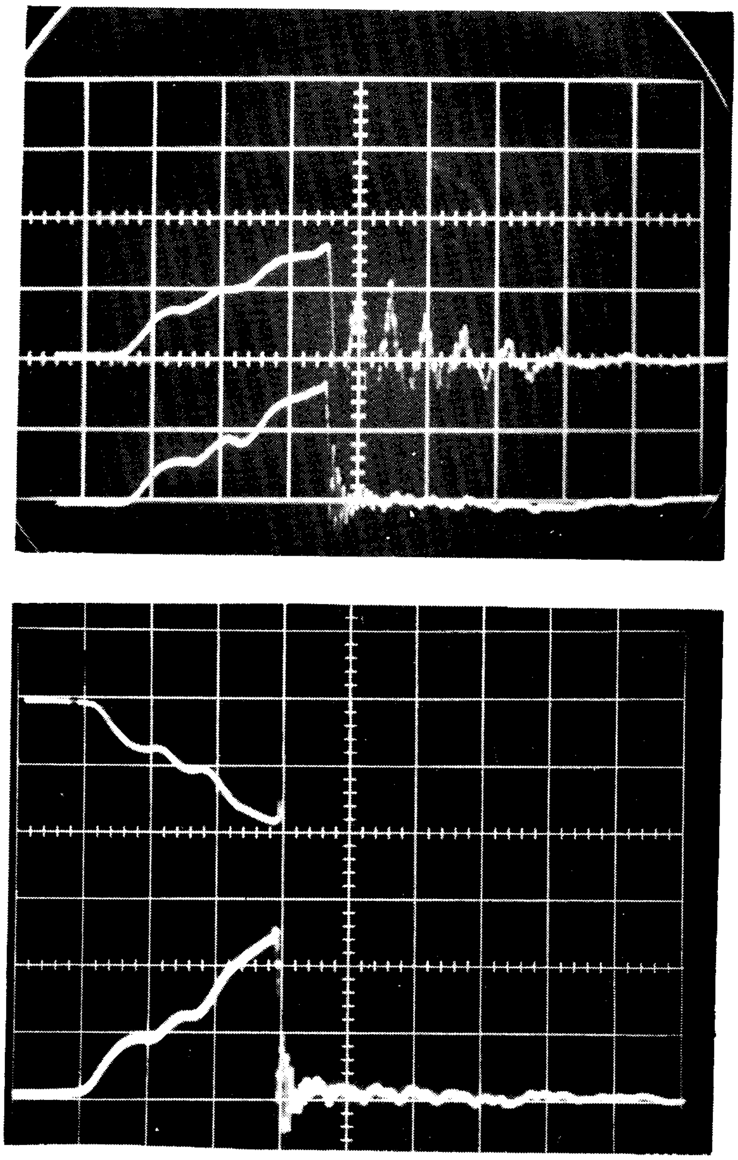


Fig. 17 LOAD AND STRAIN RECORDS FOR $[10_6]$ BORON/EPOXY OFF-AXIS SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 6.3 ε/sec.

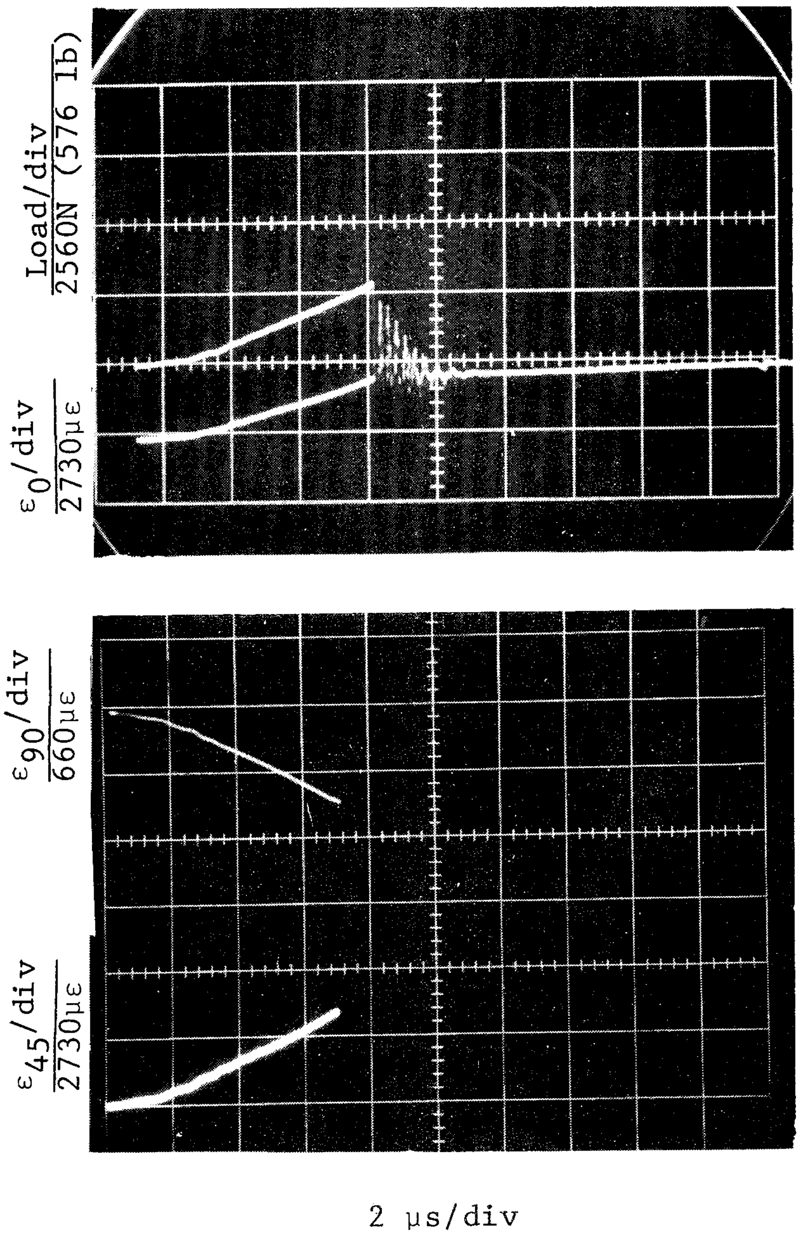


Fig. 18 LOAD AND STRAIN RECORDS FOR $[10_6]$ GRAPHITE/EPOXY OFF-AXIS SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 0.41 ε/sec.

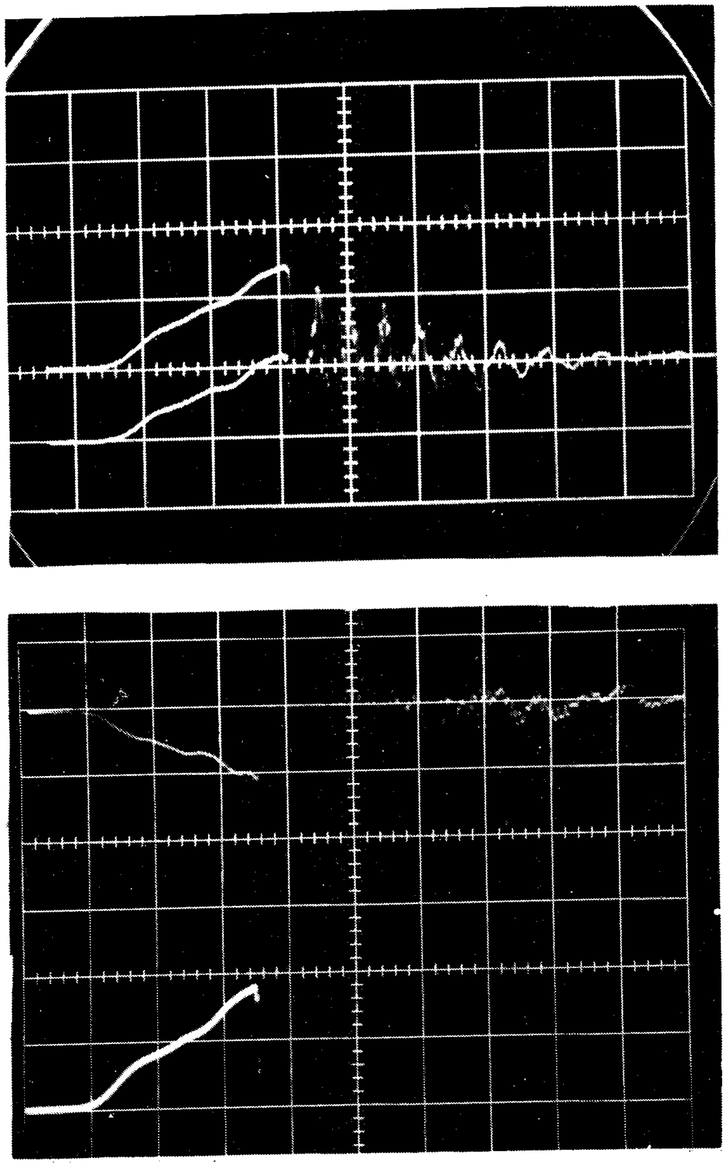


Fig. 19 LOAD AND STRAIN RECORDS FOR $[10_6]$ GRAPHITE/EPOXY OFF-AXIS SPECIMEN LOADED IN TENSION AT A STRAIN RATE OF 4 ε/sec.

REFERENCES

1. Daniel, I.M. and Liber, T., "Lamination Residual Stresses in Fiber Composites," IITRI Report D6073-I, for NASA-Lewis Research Center; NASA CR-134826, March 1975.

2. Daniel, I.M. and Liber, T., "Lamination Residual Stresses in Hybrid Composites," IITRI Report D6073-II, for NASA-Lewis Research Center; NASA CR-135085, June 1976.

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